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An estimate of the eddy-induced circulation in the Labrador Sea

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Abstract. Regions of oceanic deep convection such as the Labrador Sea are prone to baroclinic instability. The resulting geostrophic eddies play a crucial role in the post-convection adjustment process which involves both rearrangement of mass so as to release available potential energy and exchange of heat and salt with the boundaries. In this study it is proposed that the slumping of isopycnals associated with baroclinic instability drives an eddy-induced "overturning circulation" consisting of a surface intensified flow transporting low salinity water from the boundary currents into the interior; sinking motion in the interior; and an "outflow" at depth transporting newly ventilated Labrador Sea Water towards the boundaries. Typical eddy-induced velocities estimated from hydrographic data are roughly 0.5 cm/s for the surface inflow, 1 m/day for the vertical motion, and 0.1 cm/s for the deeper outflow, in close agreement with those calculated in a numerical model.

1. Introduction

The Labrador Sea is one of the few regions where open ocean deep convection occurs [*The Lab Sea Group*, 1998]. Winter time convection generates baroclinically unstable density gradients, resulting in an energetic eddy field [*Visbeck et al.*, 1997]. These geostrophic eddies may be the primary agents for communication between the interior and the boundary currents that surround the Labrador Sea, and thus play an important role in both restratification and dispersing the newly ventilated water [*Jones and Marshall*, 1997]. The eddies extract available potential energy (APE) from the large scale density field and drive, in analogy with the atmosphere's Ferrel cell, an indirect "overturning circulation". In the context of the Labrador Sea such a circulation driven by the slumping of isopycnals will transport buoyant low salinity water from the boundary currents towards the interior, and newly ventilated Labrador Sea Water at depth towards the boundaries. A schematic of this anticipated eddy-induced flow field is illustrated in Fig. 1.

2. Observing the Overturning Circulation

The eddy-induced circulation cannot be detected directly using traditional Eulerian instruments such as current meters. Instead, we make use of the notion that away from the mixed layer and in the absence of diapycnal mixing the motion is *adiabatic*,

$$\frac{\partial \sigma_\theta}{\partial t} + \vec{u} \cdot \nabla \sigma_\theta = 0 \quad (1)$$

where σ_θ is the potential density anomaly and **u** the velocity which can be split into mean ($\overline{\mathbf{u}}$) and time-varying or "eddy" ($\mathbf{u}^*$) components. For simplicity we use a cylindrical coordinate system centered in the Labrador Sea with azimuthally symmetric radial and vertical eddy-induced velocity components v^* and w^*, respectively. The corresponding Eulerian mean velocity components (including Ekman pumping) are relatively small and neglected. The mostly barotropic azimuthal velocity is of no consequence in this discussion. Note that Eulerian measurements of σ_θ can only provide information on the *component* of velocity parallel to $\nabla\sigma_\theta$. However, in the central Labrador Sea, $|\nabla\sigma| \approx \partial\sigma/\partial z$, thus allowing us to estimate the vertical component w^*,

$$w^* \sim -\frac{\partial \sigma_\theta/\partial t}{\partial \sigma_\theta/\partial z}$$

To apply these ideas, a mean annual cycle of σ_θ in the central Labrador Sea has been constructed for the 1964–1974 period (Fig. 2). In the upper 1000 m isopycnals drop by ≈200 m over a period of 7 months (April to November), implying

$$w^* \approx -10^{-3}\ \mathrm{cm\,s^{-1}} \approx 1\ \mathrm{m\,day^{-1}}$$

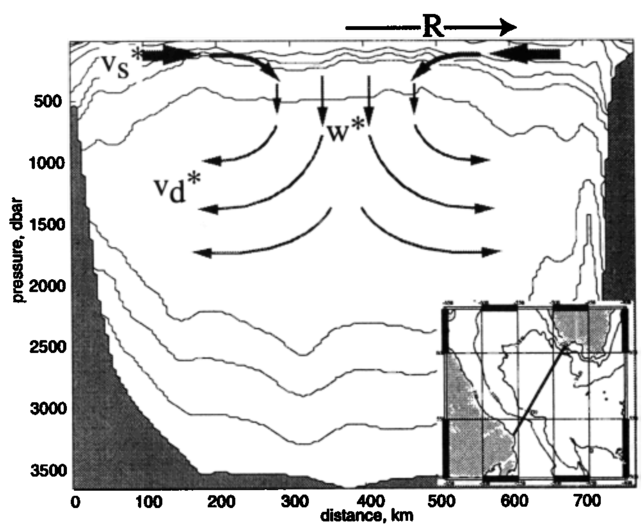

Figure 1. A potential density section across the Labrador Sea superimposed on a schematic of the anticipated eddy-induced circulation. Inset shows the position of this section in the Labrador Sea. See text for explanation of symbols.

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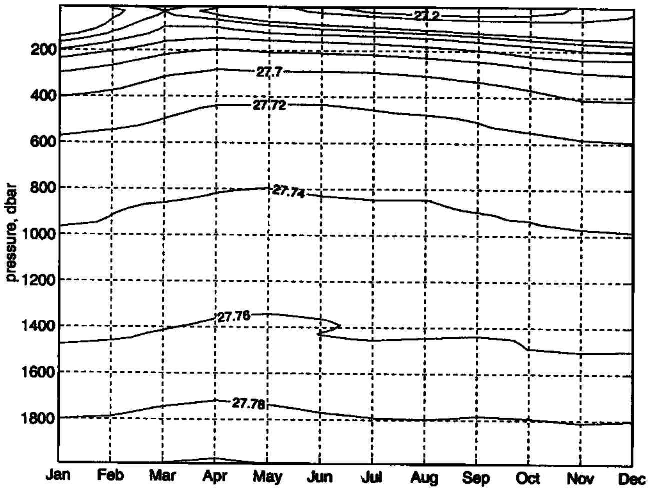

Figure 2. A climatology of potential density for the 1964–1974 period. The data were detrended before gridding to remove interannual variability.

Data from individual years give similar values for w^*. Note, that the climatology is based on a period of relatively weak convection [*Lazier*, 1995] and the overturning circulation is restricted to the upper 1000 m.

3. Inferring v^* from Continuity

The horizontal component v^* can be estimated from continuity. To apply this argument, the central Labrador Sea is modeled as a cylinder of radius R, large scale eddy-driven sinking motion with velocity w^*, near surface "inflow" with velocity v_s^* in a layer of thickness h, and deeper "outflow" with velocity v_d^* in a layer of thickness H (Fig. 1). This results in the following balances:

$$\pi R^2 w^* \sim 2\pi R h v_s^* \quad \text{and} \quad v_d^* \sim v_s^* h/H$$

Using $R \approx 200$ km, $h \approx 200$ m, and $H \approx 500$-1000 m gives,

$$v_s^* \approx 0.5 \,\mathrm{cm\,s^{-1}} \quad \text{and} \quad v_d^* \approx 0.1 - 0.2 \,\mathrm{cm\,s^{-1}}$$

The depth h =200 m roughly corresponds to the depth to which the low salinity waters from the boundary currents penetrates. H could depend on the depth of convection. For the case of weak convection considered here, a value of 500-1000 m seems reasonable.

4. Comparison with a Numerical Model

For comparison, the convective regime of the Labrador Sea has been simulated in a two-dimensional ocean model [*Visbeck et al.*, 1997] coupled to an atmospheric mixed layer model [*Seager et al.*, 1995], and configured for an azimuthally averaged domain to crudely represent a radial section across the Labrador Sea. The eddy-induced velocity is parameterized following [*Gent and McWilliams*, 1990] with a constant κ of 400 $\mathrm{m^2s^{-1}}$. Fig. 3 shows the time evolution of potential density σ_{1500} (solid) and the overturning streamfunction (dashed) representing the eddy-induced velocity field over the course of the seasonal cycle. The modeled circulation bears a strong resemblance to the schematic shown in Fig. 1. For comparison with values inferred from hydrographic data the vertical profiles of potential temperature (θ), v^*, and w^* computed by the model are shown in Fig. 4 for three different convection intensities. These are designated **HC** (depth of convection 2100 m), **MC** (1900 m), and **LC** (1700 m). The θ profile is an average for the month of March. The displayed profile of v^* is an average for the April-November period in the center of the domain (y=200 km). Similarly, the w^* profile is the mean for that period

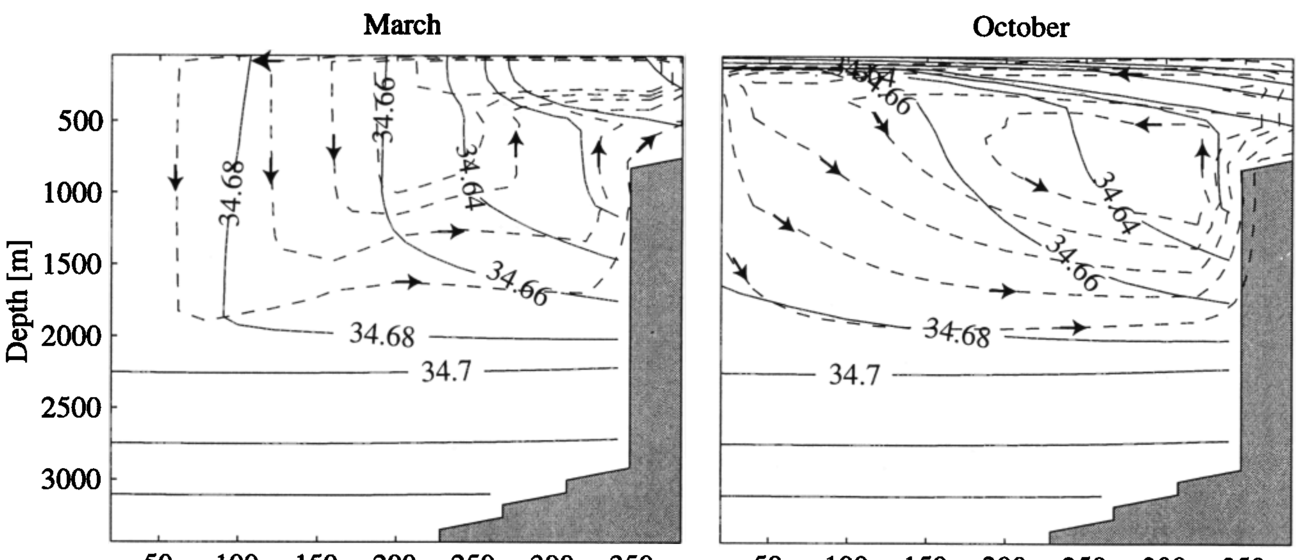

Figure 3. Time evolution of potential density (solid) and overturning streamfunction (dashed) in an azimuthally symmetric numerical model of the Labrador Sea.

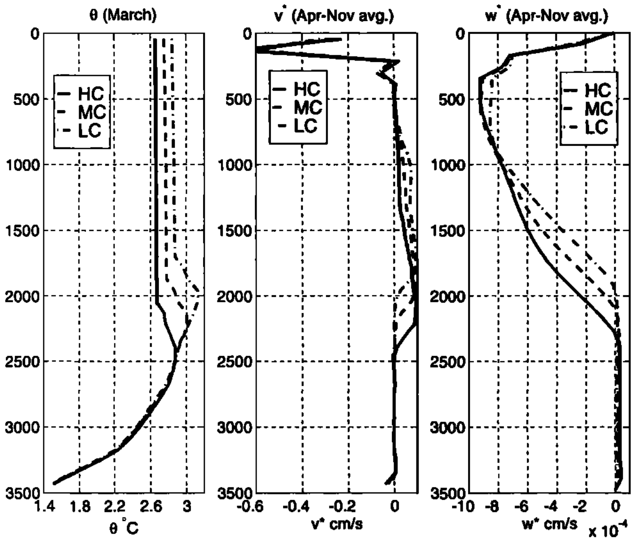

Figure 4. Profiles of θ (March), v^*, and w^* simulated in the model for three convection scenarios.

averaged from y=0 to 200 km. Gratifyingly, the mean horizontal velocity in the upper 200 m is $\approx$0.4 cm s^{-1}, similar to the 0.5 cm s^{-1} inferred for v_s^*. The deeper "outflow" velocity is of the order of 0.1 cm s^{-1}, close to the value inferred for v_d^*. Note that in these simulations the outflow occurs in a 1000 m thick layer; the depth to which it extends varies between the three cases shown, with the deepest value for the strong convection scenario. We did find that the *strength* of the eddy-induced circulation ($\approx$1.3 Sv) was insensitive to the choice of the transfer coefficient (κ) in the Gent and McWilliams parametrization. The vertical structure of the "outflow" did depend on the transfer coefficient, a larger κ leading to a greater outflow velocity, but in a thinner layer such as to keep the total flux constant.

5. Discussion

In this paper we study the eddy-induced overturning circulation using hydrographic data and a simple numerical model. Both these approaches suggest a vigorous circulation which could play a critical role in restratification and dispersal of newly ventilated water. Some of the consequences of this circulation will be now explored. 1) The eddy transport of heat into the interior of the Labrador Sea from the warmer boundary current water is essential for balancing the annual mean heat lost to the atmosphere. The time-scale on which this heat loss is balanced is of the order of a few years [*Khatiwala*, 2000] and suggests an alternative method for computing the magnitude of the eddy-induced velocity. In the framework of the cylindrical model presented above, the requirement that the lateral heat flux balance the surface heat loss gives,

$$v^* \sim \frac{QR}{2h\Delta T \rho_o c_p}$$

where, Q is the annual mean surface heat loss, ΔT is the temperature difference between the boundary (Irminger) current and the interior ($\approx$2°C), h the thickness over which the exchange takes place ($\approx$200-500 m), ρ_o a mean density, and c_p the heat capacity of water. The annual mean heat loss has been previously estimated to be between 28 and 90 W m^2 [*Smith and Dobson*, 1984]. More recent work [e.g.,NCEP Reanalyses, *Lilly et al.*, 1999] suggests a value of $\approx$50 W m^2. Substituting numerical values gives a v^* of 0.3 cm s^{-1} consistent with the value obtained earlier. 2) The implications of the eddy-driven circulation for the ventilation of Labrador Sea Water (LSW) can be considered by computing a "flushing time" τ_f using v_d^* = 0.1 cm s^{-1}, R = 200 km, and H = 1000 m:

$$\tau_f \sim \frac{\pi R^2 H}{2\pi R H v_d^*} \approx 3.2 \text{ years}$$

This value of τ_f applies to the most recently ventilated water. For the 1964-1974 period on which the climatology was based, this is the upper 1000 m to which the overturning circulation was restricted. In periods of more active convection, the overturning cell could extend deeper. This time scale for ventilation of Labrador Sea Water is similar to that given by an ideal age tracer simulated in the 2-D model. 3) The relationship between the formation rate of LSW (estimated to be around 2–4 Sv [*The Lab Sea Group*, 1998]) and the strength of the inferred eddy-induced circulation ($\approx$1.3 Sv) needs to be further explored. In particular the time scale of 3 years implied by the eddy-induced circulation if interpreted as a "storage" or "flushing" time for LSW, could impact the interpretation of transformation rates diagnosed from surface buoyancy fluxes. 4) The model results indicate that the strength of the overturning circulation (as measured by its volume flux, say) is independent of the intensity of convection, suggesting that it depends only the large-scale density distribution.

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